ANNEX B: SCIENCE REQUIREMENTS

ALMA has three level-1 science requirements:

1) The ability to detect spectral line emission from CO~~, NII~~ or C+~~II~~ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

2) The ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.

3) The ability to provide precise images at an angular resolution of 0.1". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements drive the technical specifications of ALMA. A highly simplified flow-down of science requirements into technical specifications can be given as follows:

1) High-redshift Galaxy Detection: The sensitivity of an array is primarily controlled by three major factors: total collecting area, the noise performance of the receivers, and atmospheric transparency and phase stability. The detection requirement for high-redshift galaxies, therefore has a direct impact on ALMA's collecting area, polarization and frequency requirements, and site.

   Contemporary millimeter arrays have collecting areas between 500 and 1000 m^2 and can detect CO emission from the brightest high-redshift galaxies (which are amplified by gravitational lensing), in one to two days of observations; signals from normal, unlensed objects, will be typically 20-30 times fainter. Current millimeter-wave receiver technology has approached fundamental quantum limits, and the noise level of ALMA's detectors cannot be reduced beyond this point by much more than a factor of 2; an important additional factor of $\sqrt{2}$ in sensitivity is gained by requiring that ALMA support front-end instrumentation capable of measuring both states of polarization. The proposed ALMA site will minimize the noise contributions of the atmosphere, so that the remaining factor of 7-10 in sensitivity can only be gained by increasing the collecting area of the area by a similar amount. Hence, ALMA must have at least 7000 m^2 in collecting area.

   The molecular spectral lines which generally serve as diagnostics of the gas content and dynamics of galaxies early in the history of the Universe have frequencies that are fixed in the rest frame of the galaxy, but will be observed at frequencies that depend upon redshift. Since galaxies are found at every redshift (i.e., *age*) ALMA should ideally provide access to all atmospheric windows from 30-950 GHz, so that galaxies of all ages may be studied. Initially, however, the array will support observations in the four highest-priority frequency bands. Additional capabilities may be added in the operational phase of ALMA. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers and the correlator should also be as large as possible; this will also maximize the continuum sensitivity of the array.

~~Because ALMA is an interferometer with kilometer-long baselines, the need to minimize the impact of atmospheric noise on observations requires not only a high, dry site with minimal attenuation, but also a site with high phase stability; indeed, the ALMA site has been monitored for more than 7 years in order to assure that it is optimal from both standpoints. Inevitably, however, more active measures will be required to cancel the effects of the atmospheric disturbances. To do this, each ALMA antenna will be equipped with a Water Vapor Radiometers (WVR) to measure atmospheric path length variations and correct the image distortions which such phase variations create.~~

2. Protoplanetary/Protostellar Disks: These requirements have impacts on ALMA operating frequency, baseline size, ~~and~~ frequency resolution, and polarization.~~.~~

Theoretical calculations indicate that the gaps created by Jupiter-mass objects in protoplanetary disks will be ~1 AU in extent. Combined with the distance to the nearest star-forming regions (60-15~~4~~0 pc), the requirement that such gaps be resolvable in protoplanetary disks implies an angular resolution of 0.010" or better. This can be achieved by combining high frequency ($\nu > 650$ GHz) observations with array baselines of at least 10 km. Proper study of the kinematics of the disk images further requires that spectroscopy be carried out at velocity resolutions finer than 0.05 km/s. As a result, the spectral resolution provided by the ALMA correlator must be as small as a few tens of kHz. The study of the magnetic field and its properties in disks requires that the ALMA receiving systems are equipped with full polarization capability in order to measure all the Stokes parameters.

3. Precise Imaging. The requirement for high fidelity imaging constrains the number of antennas in the array, since a sufficient number of baselines to cover adequately the *uv* plane (i.e., the time/frequency domain plane in which the data are sampled) is required. Detailed studies of the imaging performance of aperture synthesis arrays have shown that the requisite imaging performance implies a minimum number of antennas, 40 or above, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas. Such accurate measurements can only be obtained with high quality antennas, with superior pointing precision. High fidelity imaging also

requires the ability to perform calibrations to "freeze" the atmospheric turbulence which distorts the radiation coming from celestial sources.

The combination of these three major requirements calls for a reconfigurable zoom-lens array covering baselines from a few meters up to several kilometers, observing over the full millimeter and submillimeter atmospheric windows. The maximum size of the individual antennas is driven by the required pointing and surface precision: a choice of 12-m antennas offers an excellent technological compromise. To provide no less than 7000 m^2 of total collecting area, 64 antennas are needed, which is a large enough number to guarantee excellent imaging performance. Dual polarization is mandatory to provide enough sensitivity in spectral line mode. ALMA will offer a full-polarization mode to offer new capabilities to the astronomical community.

To minimize the impact of atmospheric noise, a dry site with minimal attenuation, but also with high phase stability as been selected. The ALMA site has been monitored for more than 7 years in order to assure that it is optimal from both standpoints. However, because ALMA will have kilometer-long baselines, more active measures will be required to cancel the effects of the atmospheric disturbances. To do this, each ALMA antenna will be equipped with a Water Vapor Radiometers (WVR) to measure atmospheric path length variations and correct the image distortions which such phase variations create.

The final major scientific requirement affects the diverse community that will use and benefit from the scientific capabilities that ALMA brings to extend their research endeavors: ALMA should be “easy to use” by novices and experts alike. Astronomers certainly should not need to be experts in aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the more intricate experiments requiring expert intervention.